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Research Article

Faster, broader, and deeper! Suggested directions for research on net-zero transitions

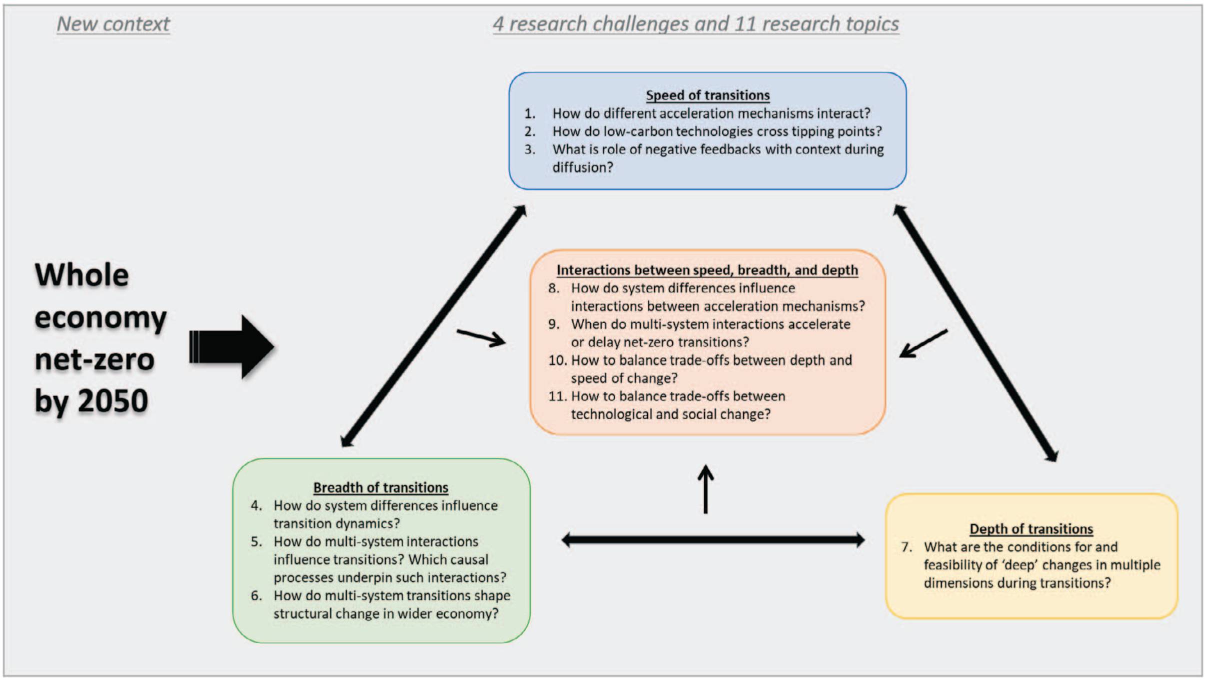
Allan Dahl Andersen[1,*], Frank W. Geels[2], Lars Coenen[3], Jens Hanson[4], Marius Korsnes[5], Kristin Linnerud[6], Tuukka Makitie[4], Amber Nordholm[5], Marianne Ryghaug[5], Tomas Skjolsvold[5], Markus Steen[4] and Kirsten Wiebe[7]

[1]Innovation Department, Senter for Teknologi Innovasjon og Kultur
[2]Manchester Institute of Innovation Research, The University of Manchester
[3]Mohnsenteret for innovasjon og regional utvikling, Høgskulen på Vestlandet
[4]Department of Technology Management, SINTEF
[5]Department of Interdisciplinary Studies of Culture, Norwegian University of Science and Technology
[6]Faculty of Environmental Sciences and Natural Resource Management, NMBU
[7]Sustainable Energy Technology, SINTEF
*Correspondence address. E-mail: allanda@tik.uio.no

Abstract

The growing attention to the political goal of achieving net-zero emissions by mid-century reflects past failures to alter the trajectory of increasing greenhouse gas (GHG) emissions. As a consequence, the world now needs to decarbonize all systems and sectors at an unprecedented pace. This commentary discusses how the net-zero challenge presents transition scholarship with four enhanced research challenges that merit more attention: (1) the speed, (2) breadth and (3) depth of transitions as well as (4) tensions and interactions between these.

Graphical Abstract



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Lay Summary: Governments, cities and companies are increasingly adopting goals of reducing GHG emissions to net-zero by mid-century to limit global warming, but concrete and credible plans to achieve these goals are largely absent. This commentary article suggests directions for research on net-zero transitions that can ultimately inform and support formulation of concrete net-zero plans. We discuss several research topics including how transitions can move faster with attention to both new technology and new social practices and ways of living the variety of systems and sectors, the interactions between them, and the social tensions that can emerge in the face of rapid change.

Keywords: transition tensions, deep socio-technical change, multi-system interactions, acceleration mechanisms, net-zero transition

A NEW CONTEXT FOR TRANSITION STUDIES

More and more governments, cities and companies are adopting climate policy goals based on achieving net-zero greenhouse gas (GHG) emissions by mid-century to limit global temperature rise. Despite the popularity of net-zero target setting, concrete plans and strategies for how to achieve the goals are largely absent [1]. It also remains a major task to translate the notion of a net-zero transition into a social science framework that can support analysis, policy design and implementation [2]. In this commentary, we therefore suggest several directions for research on net-zero transitions by sustainability transition scholars, which is a first step toward supporting decision-makers to think more systematically about strategies and policy mixes.

Sustainability transitions research understands transitions as fundamental shifts in socio-technical systems that provide important societal services like electricity, mobility or agri-food. Because socio-technical systems consist of technologies (technology covers the materiality of the system including technological artefacts, physical products and material needs), actors and institutions [3], transitions are seen as multi-dimensional, multi-actor, long-term, non-linear and co-evolutionary processes characterized by open-endedness, uncertainty and contestations among social groups, where novel and more sustainable technologies or social practices transform existing unsustainable systems for providing key societal services [4, 5].

The properties of the net-zero challenge imply four enhanced research challenges for sustainability transition scholarship. First, due to the mid-century deadline, the world needs a historically unparalleled yet purposeful acceleration of change in all major systems [2]. Therefore, transitions research should focus more on the acceleration of transitions and the rapid diffusion of technical and social innovations. Second, researchers must increasingly consider a wide variety of systems and sectors and pay more attention to multi-system interactions in transitions. Note that we see socio-technical systems as covering the elements in production, distribution and consumption domains that together fulfil societal functions. Sectors however are delineated according to a specific set of products (*e.g.* chemicals, cars, steel or electronics) or services (*e.g.* finance) [6]. The sector concept thus typically covers the production domain. Sectors produce multiple outputs that are used in systems and are therefore often upstream to systems. Third, transition research should better analyse 'deep' social changes that enable and complement widespread diffusion of low-carbon technologies. Note that we focus on a net-zero transition at the level of the whole economy. Besides social practice changes, this requires diffusion of a mix of low-, zero-, and negative-emission technologies. The reason for including negative-emission technologies is that currently, net-zero emission technologies do not exist for all systems and sectors. For simplicity, we only use the term low-carbon technology.

Although transition researchers have started to explore these aspects of net-zero transitions [*e.g.* 7], they are typically considered in isolation. We note important tensions and interactions between these processes that are crucial for understanding and governing net-zero transitions. The 'fourth' research challenge is therefore the interactions and possible tensions between speed, breadth and depth of transitions. We elaborate and discuss these research challenges in the subsequent sections and identify 11 research topics of great relevance to net-zero transitions.

THE SPEED OF TRANSITIONS

The large gap between current emission trajectories and policies and future net-zero targets [8] places accelerated sociotechnical change at the heart of the challenge of achieving a net-zero transition by mid-century. Although transition scholarship initially focused more on the emergence of low-carbon niche innovations than on rapid diffusion and upscaling, which are central to the acceleration phase of transitions [9], relevant acceleration mechanisms have nevertheless been identified in the literature. The importance of various acceleration mechanisms may vary between new technologies and social innovations, including business model innovation and social practice changes [10–12]. We present mechanisms in relation to the three socio-technical system dimensions of technology, institutions and actors.

Acceleration mechanisms in the 'technology dimension' include: 1) performance improvements of low-carbon technologies resulting from research and development or learning processes [11]; 2) cost reductions arising from economies of scale and learning-by-doing [13]; 3) availability of supporting assets such as skills, materials and finance as well as complementary technologies and infrastructures [14]. All three mechanisms make low-carbon technologies more attractive for users.

Acceleration mechanisms for the 'institutional dimension' include: 4) stronger policy support through subsidies, deployment quotas, capital grants, public procurement, infrastructure investments or regulatory changes, including phaseout policies of existing technologies like diesel cars [15, 16]; 5) changing social norms that influence user preferences in the direction of low-carbon technologies or social practices [17]; 6) the development and strengthening of visions for a net-zero society, including new technologies and social practices [18, 19].

Acceleration mechanisms for the 'actor dimension' include: 7) the reorientation of business actors leading to increased belief and investments in low-carbon technologies and business models [20]; 8) increased adoption of low-carbon technologies or social practices by consumers as solutions become better and cheaper, and as social norms change [21]; 9) formation of actor coalitions around low-carbon innovations, which lobby and exert pressure for policy change [22, 23].

Accelerated diffusion of low-carbon innovations involves positive feedback loops between these mechanisms to generate increasing momentum, as analyses of wind turbines, solar-PV and electric vehicles indicate [24]. There are, as of yet, fewer examples of accelerated diffusion of social innovations [25, 26], which often face institutional barriers and do not benefit from the technology acceleration mechanisms.

Although transition scholars have developed relevant insights for individual mechanisms, a systematic understanding of how they interact is yet to be developed (research topic 1). One issue is that the strength of acceleration mechanisms tends to be limited in the early phase of transitions when actors are often reluctant to develop, invest in and adopt novel low-carbon solutions and practices because of uncertainty, misfit with existing norms and high costs. When actors limitedly engage, these solutions do not benefit from learning effects, social network effects and cost reductions, which is why they remain stuck in small niches. A key issue for better understanding accelerated transitions is therefore to look at how low-carbon technologies can cross tipping points from negative to positive feedback loops [27, 28] (research topic 2).

Another issue is that the wider diffusion of low-carbon innovations may generate negative feedbacks with established technologies and practices, which can limit support and hamper further diffusion [29]. The German diffusion of solar-PV, for example, rapidly increased subsidy costs in the late 2000s, which led to negative socio-political debates in the early 2010s and weakening policy support [30]. Diffusion of low-carbon solutions may also directly threaten the interests of incumbent firms and trigger counter-lobbying efforts, for instance by big oil companies [31]. Understanding if and how negative feedbacks with context can influence or delay diffusion of low-carbon innovations is thus an important research topic (3).

BREADTH OF TRANSITIONS

In this section, we discuss two issues: types of systems and sectors and multi-sector interactions. First, a net-zero transition implies increasing the scope of decarbonization efforts to include all systems and economic sectors. Transition researchers have traditionally focused mostly on energy and transportation systems because transitions are unfolding in these systems through the diffusion of solar-PV, wind turbines and electric vehicles. However, grasping the net-zero challenge requires more attention to qualitatively different 'types of systems' (*e.g.* aviation, shipping) and upstream 'sectors', including mining, chemicals, cement and construction.

Such broadening involves better theorizing about how systems and sectors differ and what this implies for transition patterns [32, 33] (research topic 4). In terms of 'institutions', diverse institutional logics and regulatory environments may, for example, lead to different innovation and transformation modes across systems [6, 34]. In terms of 'technology', there are differences in capital intensity, which shapes strength of lock-in mechanisms, and in the cumulativeness of knowledge and technological opportunities, which leads to different modes of innovation [35, 36]. In addition, transitions in some systems involve the diffusion of small-scale technologies such as heat pumps or electric bikes, which tend to benefit from steep learning curves and cost-reduction trends [10]. In other systems and upstream sectors, large-scale, capital-intensive technologies are needed, such as shifts to hydrogen in the steel sector or carbon capture and storage (CCS) in the cement sector [11]. Moreover, some solutions can build on existing infrastructures (*e.g.* heat pumps and electric vehicles can align with existing electricity systems), whereas others such as CCS and hydrogen require the building of new infrastructures, which is challenging [37]. In terms of 'actors', the constellation, number and types of actors differs substantially between systems, leading to different innovation and transition patterns [6, 38].

Second, not only do net-zero transitions involve changes in all systems and upstream sectors, but they also imply that those changes must happen in parallel to meet the mid-century deadline. Interactions and feedbacks between multiple systems and sectors will therefore be essential in net-zero transitions [39–41]. For example, many low-carbon technologies depend on innovations in and expansion of upstream sectors, such as semiconductors or mining. Currently, for instance, scarcity of raw materials such as lithium threaten to slow down the upscaling of electric vehicle production [42, 43]. Similarly, widespread low-carbon electrification, *e.g.* in transport, heating or industry requires that electricity is available in the right volume, place and time, which often involves expansions of renewables, grids and/or use of new technologies [44, 45]. Moreover, a net-zero transition implies the diffusion of several multi-purpose technologies—*e.g.* carbon capture, batteries, or artificial intelligence—that interconnect and play vital roles in multiple system transitions [46–50]. Lastly, the financial sector sits centrally in the web of cross-sectoral interactions. Understanding how the financial sector exerts major influence on all system transitions and whether a transition within finance itself is happening or needed are important topics for future research [51, 52].

The challenge of 'breadth' thus requires transition research to focus more on the interactions across multiple systems and sectors in the course of a focal system transition, and especially the processual dynamics of the multi-system interactions—*e.g.* how they emerge, stabilize and decline—to grasp its politics and actor strategies [53] (research topic 5). Moreover, the net-zero ambition calls for thinking beyond single-system transitions and consider how a net-zero transition involves co-evolving changes in a patchwork of systems and sectors generating structural change in the whole economy (research topic 6).

DEPTH OF TRANSITIONS

Achieving net-zero decarbonization across multiple systems and sectors may also require deep social and technological change. Several scholars argue that technological change in itself, although crucial, will be insufficient to realize a net-zero transition. In addition, profound social changes in lifestyles, practices, business models and values across the entire society are needed [54, 55]. Such changes can reduce consumption of energy and materials thereby reducing the challenge of decarbonization. Indeed, some argue that without such deep social change, net-zero transitions will be so material-intensive that several planetary boundaries will be breached [56]. The needed expansion in material extraction alone may prohibit sufficient diffusion of low-carbon technology by mid-century [57].

Geels and Turnheim [24] recently proposed to understand the depth of transitions as degrees of deviation from existing system configurations, seen as how many dimensions are changing (technology, institutions, actors) and how deep change within each dimension is. We further elaborate the three dimensions as follows.

In terms of 'technology', some low-carbon technologies like insulation or extensive recycling rely on knowledge bases that are only incrementally different from the existing ones, whereas others radically differ and require development of entirely new knowledge bases. Technologies may also differ regarding whether new complementary technologies or entire infrastructures are needed for their deployment. For example, the challenge of integrating variable renewables can require a fundamental shift in needed complementary technologies such as battery storage and smart grids [58], and CCS requires entirely new infrastructures.

In terms of 'institutions', diffusion of low-carbon technologies and practices can require varying degrees of change in existing institutions such as policies, norms and visions. For example, Norway has experienced widespread diffusion of electric personal cars to reduce GHG emissions. However, there has been only limited change in how and how much cars are used [59]. The reason is that the car is embedded in a nexus of social practices related to, *inter alia*, urban design, job commute, daycare routines, grocery shopping and so on [60]. Examples of transitions that require deeper institutional change include shifts to circular, sharing or 'sufficiency' logics, which depart from established norms of mass consumption, private ownership and more-is-better to envision an ecologically safe and socially just space where humans can lead good lives within planetary limits [61, 62].

In relation to 'actors', different depths of actor reorientation in transitions can be identified ranging from changes in a) routines and b) capabilities to c) values, mindsets and world views. These increasing depths of change apply to different actor groups such as firms, consumers and policymakers. For example, the diffusion of EVs requires changes in consumer 'routines' (*e.g.* regarding when, how often and where you recharge/refill) and the development of 'new capabilities' by automakers and repair shops. A transition toward a sufficiency or degrowth paradigm would require not only new low-carbon vehicles but also profound changes in 'values, mindsets, and worldviews' in all actor groups to radically reduce the volume of travel and make it more collective [58].

Transition scholarship has traditionally assumed that deep transformative change is defining for a transition [see *e.g.* 5, 63] but several contemporary success stories—such as diffusion of EVs and renewables (wind and solar)—do not necessarily require deep changes in all dimensions. For instance, based on an analysis of 22 low-carbon technological innovations across electricity, mobility and heating systems in the UK, Geels and Turnheim [24] conclude that rapidly diffusing technologies (*e.g.* renewable energy and electric cars) involved significant changes in mindsets and capabilities of firms and policymakers (*e.g.* more interventionist logic) but only limited changes in user practices.

Future transitions research should thus pay more attention to the feasibility and conditions for deep changes in multiple dimensions (research topic 7). Although socio-technical transitions research has long called for analysing both technical and social practice changes [64], it is ultimately an empirical question to assess to what degree deep technical and social changes are happening in real-world net-zero transitions.

INTERACTIONS BETWEEN SPEED, BREADTH AND DEPTH

We note several important interactions and tensions between the speed, breadth and depth of transitions. These also constitute an important research challenge for analysts and practical challenges for decision-makers.

Speed-breadth

A first point in relation to 'breadth' is that due to qualitative system differences, the acceleration mechanisms we discussed previously likely differ in how they manifest themselves across systems and upstream sectors (research topic 8). For example, products like steel or cement are not as directly visible and exposed to pressures from the general public and end-consumers as compared with consumer products like electric vehicles. The role of consumer interest and changing societal norms (mechanisms 5 and 8) will thus likely play a lesser role in the steel and cement sectors. Moreover, upstream sectors like cement and steel are dominated by a few large, powerful firms operating in international markets with limited possibility for new entry. Sectors like construction or transport services (*e.g.* ferries) are characterized by multiple smaller actors operating in local markets with higher entry/exit rates. The type of networks, coalitions and politics characterizing these systems and sectors will differ as will the type of policy instruments needed to support their transition (mechanisms 4 and 9).

A second point in relation to 'breadth' is that due to system differences, new multi-system interactions can create tensions that manifest as contrasting institutional logics, conflicting actor interests, limited mutual understanding or technical incompatibilities [65, 66]. Acceleration mechanisms can thus expand beyond a focal system. Regarding upscaling of value chains, for example, expansion of upstream mining sectors is typically slow, whereas expanding production of EVs can be rapid. A new mine can easily take 10 years from investment decision until operation [42] and high upfront capital costs make mining firms conservative and relatively unresponsive to short-term changes in demand [67] (mechanism 2 and 3). Expanding mining operations can moreover create pollution and poverty in source regions [68], which can undermine the sustainability promise and legitimacy of low-carbon technologies for consumers and the wider public (mechanisms 4 and 8). Regarding the provision of low-carbon electricity, there are land use conflicts in many places that lead to opposition toward expanding power production and grids to ensure electrification (mechanism 3 and 5).

However, solutions can also be provided by other sectors. For instance, the electrification of transport can be faster if vehicle-to-grid services are successful because this can reduce the need for building new grids [69]. Furthermore, material scarcity may be mitigated by stronger interactions with waste management and circular economy approaches [70]. Multi-sectoral interactions can thus both slow down and accelerate transitions. As a consequence, we need a better understanding of how interactions between transitions can have accelerating effects and how tensions between multiple systems and sectors can be mitigated through policy measures (research topic 9).

Speed-depth

In relation to 'depth' of change, we note several potential tensions between depth and speed of change. In terms of 'technology', it is obvious that acceleration mechanisms (*e.g.* 1, 2 and 3) will be more difficult to enact if technologies are radically new, have limited production scale (*e.g.* due to high customization) and if complete, new complementary assets are needed for their diffusion. More generally, there is a tension between speed of change and possibilities for learning and experimentation [71] such that rapid responses may tend to rely on existing knowledge.

In terms of 'institutions', innovations that require deeper institutional change (*e.g.* car sharing or demand-side response) often face many barriers and diffuse slowly [24]. This suggests that there may be tensions and trade-offs between the depth of institutional change and speed of change (mechanisms 4, 5 and 6). In terms of 'actors', deeper changes tend to be more difficult and slower, so on this dimension, there are also tensions between depth and speed of change (mechanisms 7, 8 and 9). These insights suggest that the more system dimensions that need to change and the deeper the changes, the more tensions there will be with the rapid diffusion of a low-carbon technology (research topic 10).

Tensions have historically been mitigated through experimentation, participatory democratic discussion and stakeholder negotiations in learning-by-doing implementation processes. But these processes are often slow, which thus creates trade-offs with the urgency of the climate crisis [72, 73]. Conversely, downplaying or sidelining these processes may create citizens' acceptance problems for low-carbon solutions, potentially slowing down the transition [74]. Just transition strategies that aim at 'leaving no one behind' in the net-zero transition—such as the proposed European Green Deal—will thus need to balance such trade-offs.

Breadth-depth

In terms of interactions between breadth and depth of change, we note that if it proves difficult to realize broad complementarities between multiple upstream sectors (to enable upscaling of production capacity for new low-carbon technologies), the need for deep social change (to reduce consumption levels for energy, materials and services) will grow proportionally. For example, if slow or unsustainable expansion of mining for critical materials limits EV diffusion, alternative solutions may become more important such as car-sharing or shifting mobility to other modes (such as collective transport or bikes) or reorganizing societies to reduce the need for transport altogether [43, 75]. Similarly, if deep social change to reduce consumption levels proves unachievable, rapid upscaling of upstream production sectors becomes even more crucial.

Overall, there is a research need for better understanding interactions and tensions between depth, breadth and speed of transitions across different places, technologies and systems. Are there, for instance, examples of deep, broad and rapid changes (at large scale)? If so, what lessons can be drawn from this?

CONCLUSION

This commentary has shown that net-zero transitions pose four enhanced research challenges for sustainability transition research—understanding speed, breadth and depth of transitions and the interactions and tensions between them—that led us to identify 11 more specific research topics. We suggest that a key future task for transition scholarship is to deepen the theoretical, methodological and empirical knowledge about these particularities of net-zero transitions. Research on tipping points, synergetic multi-system interactions, system differences and tensions are particularly fruitful avenues. Transition scholars should also identify new ways of dealing with these tensions to strengthen the toolbox available to decision-makers and improve our chances of reaching net-zero emission goals by mid-century.

Ending on a reflexive note, we observe that the goal of net-zero GHG emissions by mid-century emerged because of insufficient actions in the past, which forced policymakers to adopt more ambitious targets (like net-zero) and led integrated assessment modelers to propose more radical solutions in terms of technologies (*e.g.* negative-emission technologies) and diffusion rates, which some experts find unlikely [76, 77]. This means that we should not assume that the net-zero target will necessarily be met. Because many of the challenges we discussed are daunting, failure is certainly possible. In fact, some of the speed, depth and breadth challenges are not dissimilar to those associated with 80–90% GHG reduction targets, but they are intensified and augmented by more radical policy goals, which is why we mostly referred to enhanced research challenges. Because few countries are on track to meet their climate mitigation targets, a final topic for transitions research could be policy failure and how policymakers can use amended and increased targets to hide those failures by creating smoke screens and policy bubbles [78].

Supplementary Data

Supplementary data are available at Oxford Open Energy online.

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Authors' Contributions

A.D.A. and F.W.G. contributed to conceptualization; original draft writing; and writing, review and editing. L.C., J.H., M.K., K.L., T.M., A.J.N., M.R., T.M.S., M.S. and K.S.W contributed to writing, review and editing.

Data Availability

There are no new data associated with this article.

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